Research Article

Prediction of Indian summer monsoon onset with high resolution model: a case study

Devaraj Rajan[1] · **Srinivas Desamsetti**[1]

Received: 3 November 2020 / Accepted: 5 May 2021
Published online: 17 May 2021

Abstract
India is an agro-based country, receives nearly 80% of the annual rainfall during the summer monsoon season, and has a vital socioeconomic security link. The start of the Indian rainy season is observed over the country's southern tip (Kerala) and is referred to as the monsoon onset. The Indian Summer Monsoon (ISM) onset is one of the key aspects and unique for each year. This paper aims the prediction of ISM onset for different years by using the operational numerical weather forecasts at medium-range time scales by using different atmospheric variables from UKMO, and NCMRWF deterministic (NCUM) and ensemble model (NEPS) weather forecasts. For predicting the 2018 onset, we have adopted objective methods like the rainfall criteria, daily circulation index, potential temperature, moisture transport etc. The results for an early onset year (2018) show that the models could predict the onset date agreeing with the observed India Meteorological Department (IMD) onset date of 29 May 2018 from both UKMO 5-day and NCUM 10-day forecasts. This study also emphasizes on the utilization of the medium-range numerical weather forecasts, providing enough time to plan the farming activities. We also present the models' performance/ skill for assessing the onset dates for the delayed onset (2019) and timely onset (2020) monsoons with NCUM 10-days lead time, and the results agree with IMD dates. From the UKMO, NCUM, NEPS models' rainfall forecast show that the onset date on 29 May 2018 as IMD. Similarly, the analysis from circulation index, potential temperature, vertically integrated moisture transport analysis, outgoing long wave radiation, tropospheric temperature index clearly shows the onset date agreeing with IMD observations. Similarly, for the late onset (2019) and timely onset (2020) years, the daily circulation index agrees with IMD observed onset dates. Finally, these results from the deterministic and probabilistic forecasts are consistent with the observed onset dates, and these medium range forecasts are highly helpful to compute the monsoon onset date with higher lead times (10 days) within the error of one day.

Keywords Indian summer monsoon · Onset · Unified model · Medium range forecast · Ensemble forecast · Monsoon indices

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42452-021-04646-w.

✉ Devaraj Rajan, drajan@ncmrwf.gov.in; Srinivas Desamsetti, srinivas@ncmrwf.gov.in | [1]NCMRWF, Ministry of Earth Sciences, A-50 Sector-62, Noida, U.P., India.

1 Introduction

The Indian summer monsoon onset over Kerala represented the start of the Indian rainy season (June–September). It is also referred to as southwest monsoon or Indian summer monsoon (ISM), as it covers over 80% of the total annual rainfall [1]. India experiences a highly versatile kind of weather around the year. The summer monsoon season starts typically on 1 June every year over Kerala and covers the entire country by 8 July, and India receives the monsoon rains till the end of September [2]. Some interesting information about the onset date is (i) the earliest onset date is 18 May 2004, 19 May 1990 (ii) the latest onset dates are 13 June 1983, 13 June 1979, 18 June 1972. The Indian monsoon regularity is only in its annual recurrence, but its basic characteristics like onset, total seasonal rainfall, withdrawal, etc., have a large variability with the same gusto. Prediction of monsoon onset is crucial in India for agricultural planning to start the sowing, as it is connected to the food production for more than a billion people over India. The onset of ISM is generally associated with the rainfall from the deep convection clouds over a large area. It extends from the southern Arabian Sea to the north Indian Ocean region [3]. The moisture carried from the southern Indian Ocean to the convective heat source over the Arabian Sea along with a strong cross-equatorial flow, also referred to as the low-level jet, sets the beginning of the Indian monsoon, and further progress over the entire Indian region [4, 5].

India Meteorological Department (IMD), an operational weather forecasting agency in India, developed the isopleths of normal dates of onset over the India region [6] back in 1943, and every year the progress of monsoon is being depicted on the normal dates chart https://mausam.imd.gov.in/imd_latest/contents/monsoon.php. Many studies are attempting the prediction of onset over Indian region e.g., [5, 7–10]. However, recently IMD updated the onset and withdrawal dates with new subject-based methods [11].

IMD uses the following criteria for declaring monsoon onset over the country. Firstly, rainfall should be widespread over Kerala, and adjoining areas with rainfall amounts persist over several days. More precisely, the rainfall amount 2.5 mm or more for two consecutive days over 60% of the available 14 stations over Kerala and adjoining regions (Kannur, Kudulu, Mangalore, Minicoy, Punalur, Kollam, Allapuzha, Kottayam, Kochi, Thrissur, Kozhikode, Thalassery, Amini, Thiruvananthapuram), and the onset would be declared on the second day. The second, the depth of westerlies in and around Kerala, should be strong (15–20 kts) and maintained up to 600 hPa between 0° and 10° N and 55° and 80° E. Finally, the air should be highly humid up to a depth of 500 hPa level.

IMD predicts the ISM seasonal rainfall, using statistical, empirical methods and recently using the numerical models at a seasonal scale in April and being updated in June. The timing of monsoon onset is essential to the farmer's sowing phases, agricultural sector, water replenishment, etc., hence it is a high priority for an operational weather forecaster to develop a subjective method to predict the onset of monsoon. Different empirical methods are being used to predict the monsoon onset based on the rainfall, upper-level winds, and radiation. The Indian subcontinent changes during the onset phase of ISM over India as a rapid increase in the daily precipitation increased vertically integrated moisture and low-level kinetic energy [12]. [13] estimated the onset date for south and northern Kerala separately, as the first day of transition from light to heavy rainfall. The condition that the daily rain of the first pentad and after the transition should not be less than 10 mm, and [14] studied the ISM onset related to the temperature increase over Tibetan Plateau from May–June due to the reversal of land-sea thermal contrast. [15] looked at the south of the Tibetan Plateau; the reversal of large-scale meridional temperature gradient in the upper troposphere connected with the ISM onset and proposed an index based on the methodology. [5] proposed an index based on the low-level winds over the southern Arabian Sea. [16] identified a decrease in tropopause height and increased temperature during the onset. [11] developed principal component regression based objective methods by using large scale circulation parameters and rainfall as predictors to predict the monsoon onset. [17] computed the monsoon onset using the onset circulation index using the Coordinated Regional Climate Downscaling Experiment (CORDEX) models weather parameters. [18] developed an objective method for real-time extended-range prediction of the monsoon onset using rainfall and low-level winds as predictors. [19] assessed the performance of regional climate model in simulating the Kerala monsoon onset for 30-year period long simulations at 25 km horizontal resolution and found that model performed better for normal and delayed onset years than the early onset years.

In Numerical Weather Prediction (NWP), numerical models are being used to predict the weather at the short (up to 3-days), medium (up to 10-days), and extended range time scales (up to a month). NCMRWF scientists evaluated the monsoon features for 2017 and 2018 with NCMRWF global deterministic model (NCUM) and ensemble model (NEPS). They showed that the models could predict the monsoon flow pattern and rainfall activity very well with a 5-day lead time. [20] assessed the NCMRWF global ensemble prediction system's skill and reported that the NEPS show high predictive skill up to 7 days during monsoon 2018. [21] evaluated the UKMO model precipitation forecast from UKMO model during monsoon season of 2007–2015. NCMRWF, the operational weather forecasting center, generates weather forecasts daily using deterministic and dynamical ensemble models valid for the next 10 days. Here we examined the fidelity of monsoon onset date over the Kerala coast with various geophysical parameters available/predicted by the dynamical models. A variety of monsoon indices are computed to predict ISM's onset at a medium-range time scale using both the NCMRWF deterministic and ensemble model forecasts. In the present study, the NCMRWF NWP models' forecasts adopted for predicting the 2018 monsoon onset, employing the objectively defined methods. The rainfall, temperature, winds at different levels, and outgoing long-wave radiation are the generally substituted parameters in these methods. India, such a vast nation, needs planning for agricultural operations when to start, as agriculture primarily controls the Indian economy. Hence the forecasting the onset date is very crucial here to start the sowing. In this context, it is essential to know the monsoon's onset at least a week in advance with high accuracy. So, we archived the deterministic and ensemble models' forecasts originated at NCMRWF for predicting the Indian summer monsoon onset with 10 days lead time for the 2018 monsoon (early-onset). The results authenticate the objective methods to detect monsoon's onset and can be used by any other organization. We also followed a similar exercise to observe the onset date for 2019 (delayed onset) and 2020 (timely onset) monsoons. Generally, these objective methods use weather variables from analysis, but we used the forecasts as input variables. NCMRWF uses the advanced data assimilation system for operational use. Hence this study also reveals the assimilation and forecasting system capability during the early, timely, and late monsoon onset. The present study shows the usability and the skill of the state-of-art global NWP model forecasts for predicting the Indian summer monsoon onset.

Onset date forecast over Kerala is helpful to know the entry of monsoon over the Indian subcontinent. The study mainly focuses on the dynamical operational numerical model forecasts and their usage to predict the onset of the Indian summer monsoon. Different monsoon onset criteria are addressed in the present study using the numerical model forecasts at medium-range time scales. Here both the operational dynamical model predictions at NCMRWF (NCUM, NEPS) and United Kingdom Met Office (UKMO) are used to address the monsoon onset 2018 (early onset) by adopting objective methods. We also evaluated the onset for the years 2019 (delayed onset) and 2020 (timely onset). The present work organized as follows; Sect. 2 describes the various methodologies/criteria and datasets used in the study. Section 3 covers the results and discussions of the computed/calculated onset dates. The work summary follows it, emphasizing the rainfall distribution in Sect. 4 and the conclusions in Sect. 5.

2 High resolution dynamical models

In recent years, state-of-the-art NWP models have been developed to forecast the meteorological parameters over different spatial and temporal scales. In this section, information about the numerical model, details of datasets, types of observations used for the present study are described.

2.1 Model configuration and data sets used

NCMRWF implemented a high-resolution unified global model (NCUM) analysis and forecasting system jointly with the United Kingdom Met Office. The NCUM global high-resolution model analysis and forecasts used in this study. NCUM model is a global atmosphere model which includes semi-implicit, semi-Lagrangian dynamical core. This global model has a temporal resolution of 7.5 min, which is the minimum time step while doing model integration. It has embedded with a mass flux convection scheme with an unstable boundary layer scheme. This high-resolution model has a prognostic cloud physics scheme for the formation of rainfall. NCUM is a step towards developing a seamless forecasting platform for various applications at different temporal and spatial resolutions through a single-window modelling framework. This model is also serving as a nucleus to the NCMRWF ensemble prediction system (NEPS). NCUM is modular in nature and can be adjusted from regional to global scale [22, 23]. NCMRWF generates forecasts daily, which are valid for the next 10 days using dynamical models of NCUM and NEPS. NCUM is a global model with a horizontal resolution of ~ 17 km, having 70 vertical levels, with a 4-dimensional variational (4D-Var) data assimilation system [24]. The model configuration includes global, regional, coupled deterministic NWP systems and the NEPS.

The global ensemble prediction system of NCMRWF in 2018 was a 17 km horizontal resolution system that had been operational. This probabilistic dynamical model initial condition generated by the Ensemble Transform Kalman Filter method. These model uncertainties are taken care of by stochastic kinetic energy backscatter and random parameter schemes. In this model, 22 ensemble members getting updated for four cycles valid at 00, 06, 12, and 18 UTC every day. It is understood that an ensemble of numerical forecasts from slight perturbed initial conditions can be valuable input on the skill of the forecast using ensemble averaging. The key aspect of an ensemble strategy is the generation of initial perturbation. It is known that averaging the ensemble forecasts yields a mean forecast better than the control forecast. More details of the NEPS system can be found in [23]. NEPS model is used for probabilistic forecasts, whereas NCUM is used for deterministic forecasts. During the monsoon 2018, the real-time global model forecasts based on NCUM and NEPS were used to monitor and predict the onset, advancement, withdrawal, etc. The Indian National Satellite (INSAT-3D) derived outgoing long-wave radiation (OLR) data is archived during the study period.

In the present study, the model forecasts from UKMO (up to 5-days), NCUM and NEPS (up to 10-days) modeling systems available at 17 km horizontal resolution are used to predict the 2018 ISM onset. The UKMO model also has a similar model configuration as NCUM, but with a different data assimilation system [24]. This study also reveals the impact of the forecasts from other modeling systems during the monsoon period.

The following ground-truth observational data sets are used for the validation of model forecasts in this study. Some of the reports referred here (i) the national agency IMD daily weather bulletins; (ii) press release from IMD; (iii) reliable/actual list of climatological onset dates from IMD; (iv) high-resolution daily rainfall data over the Indian region compiled by IMD [25]; (v) daily NCMRWF & IMD rainfall analysis which is being carried out on routine basis [26] and archived for the research study; (vi) the rain gauge observations reported for 15–31 May 2018; (vii) the weekly/daily press release issued by IMD, bulletins about the current weather status, and outlook for the next two weeks.

2.2 Methodology

In this section, we describe the criteria for the declaration of the monsoon onset dates. Here IMD adopted a new methodology, and the criteria used mainly rainfall and large-scale circulation patterns, as shown by [27]. During the onset of the monsoon over India, significant changes occur in the large-scale atmospheric structure over the monsoon region. Some of the prominent features like rapid increase of daily precipitation, vertically integrated moisture, and increased kinetic energy in the lower levels [28] are being used here. The existing climatological normal dates based on rainfall data (from 1961 to 2019) and isochrones of southwest monsoon onset shown in Fig. 1, which is referred to as the Northern Limit of Monsoon onset [11]. Indian summer monsoon normally sets in over Kerala around 1 June. As per the new normal dates, the monsoon sets over Kerala around 1 June and covers the entire country by 8–10 July [11]. These onset dates of isochrones are taken from IMD https://mausam.imd.gov.in/. The objective definition of monsoon onset and its advancement [11] is one of the necessary building blocks for monsoon meteorology. Rainfall, wind, and long-wave radiation data have been traditionally used for identifying the monsoon onset. It is noted that monsoon onset dates may vary significantly temporally (year to year) and spatially (place to place). The following methods briefly describe the relationship between the ISM onset and the meteorological parameters.

2.2.1 Rainfall criteria

The onset date may arrive only after 10 May. Minimum 8 out of 14 above referred stations should report 2.5 mm minimum rainfall for two consecutive days. On the second day, the onset may be declared, along with the following criteria are also satisfied in concurrence. From the NCUM, NEPS, and UKMO model forecasts, the nearest grid point rainfall values are extracted corresponding to the observations' locations.

2.2.2 Wind field criteria

For the period 15–31 May, the zonal component of winds at 600 hPa (***U600***) are extracted and averaged for the region of 0°–10° N and 55°–80° E. Similarly, the area average of zonal wind at 925 hPa (***U925***) is also computed for the region of 5°–10° N and 70°–80° E.

2.2.3 Radiation criteria

The Outgoing Longwave Radiation (OLR) should be below 200 W/m^2 in the box confined by 5°–10° N and 70°–75° E, then onset is declared.

3 Results and discussion

Starting from the monsoon season, NCMRWF has been providing the monsoon onset dates on daily basis to the IMD forecasting division. These onset dates are based up on the well-known popular monsoon indices theories. These indices are computed from different dynamical models available at the centre. IMD's operational monsoon onset date forecast for few years has been examined in our earlier study [29]. The onset date with reasonable accuracy predicted in advance with the NCMRWF operational weather forecast model. NCMRWF monitored the dynamical indicators of onset. In the present study, the onset date for the 2018 monsoon has been examined and validated

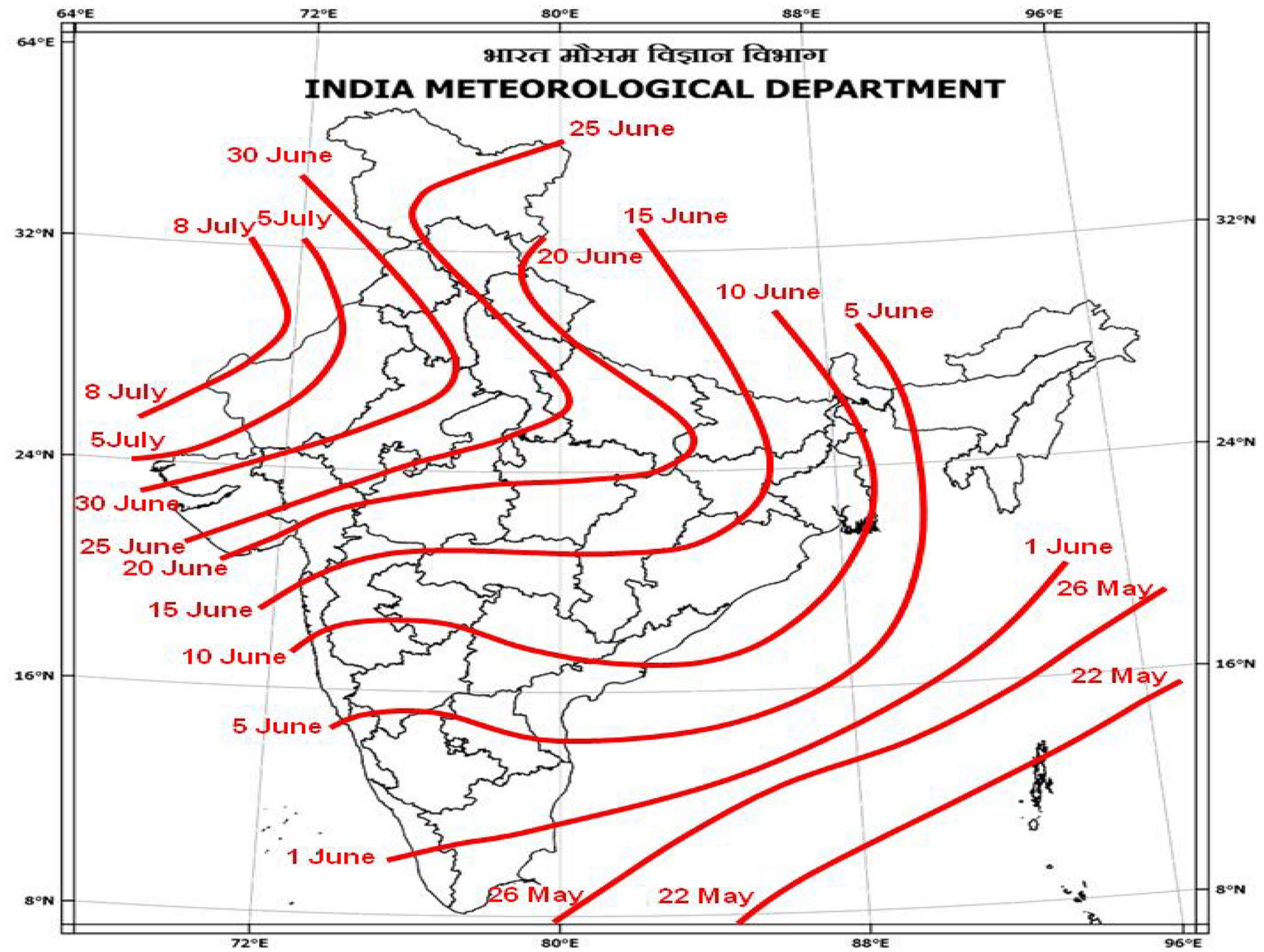


Fig. 1 Climatological normal dates and isochrones of onset of southwest monsoon [11]

through various dynamical operational models based on different criteria. This section clearly describes the use of the objective methods in assessing the monsoon onset date.

3.1 Based on rainfall criteria

As a matter of fact, there are several definitions of the onset date of monsoon over Kerala. The monsoon's arrival over the area confirms by the persistent, widespread, and heavy rainfall, which switches the occasional pre-monsoon rains. It is known that the average date of onset over Kerala is 1 June; onset over Andaman Sea is 20 May, for north-eastern states is 5 June, and it covers entire country by 8 July (Fig. 1). In the same line, IMD defines onset dates on various locations, following the criteria described above.

The NCMRWF receives global meteorological observations through the global telecommunication system via a regional hub placed at IMD, Delhi. With this communication system, the rain-gauge observations are made available at the NCMRWF data section. The observed rainfall time series for 14 stations during 15–31 May 2018 is presented in Fig. 2a. The figure shows most of the stations received rainfall below 2.5 mm/day until 25 May and gradual rise after that, and almost eleven stations crossed 2.5 mm/day threshold on 28 May and 29 May; hence IMD declared the onset on 29 May. The results depict the model forecasts are similar to the observations. Here the rainfall obtained from 10-day forecasts of NCMRWF dynamical models (NCUM, NEPS) is employed to compute the onset date.

We extracted the data for the 14 stations using the nearest gird-point method from the model forecasted variables. Figure 2a, b, c show the rainfall data corresponding to rain-gauge observations, NCUM global model 10-day forecast, and UKMO model 5-day forecasts, respectively. From these figures, 12 stations from NCUM and 11 stations from UKMO are raining with a

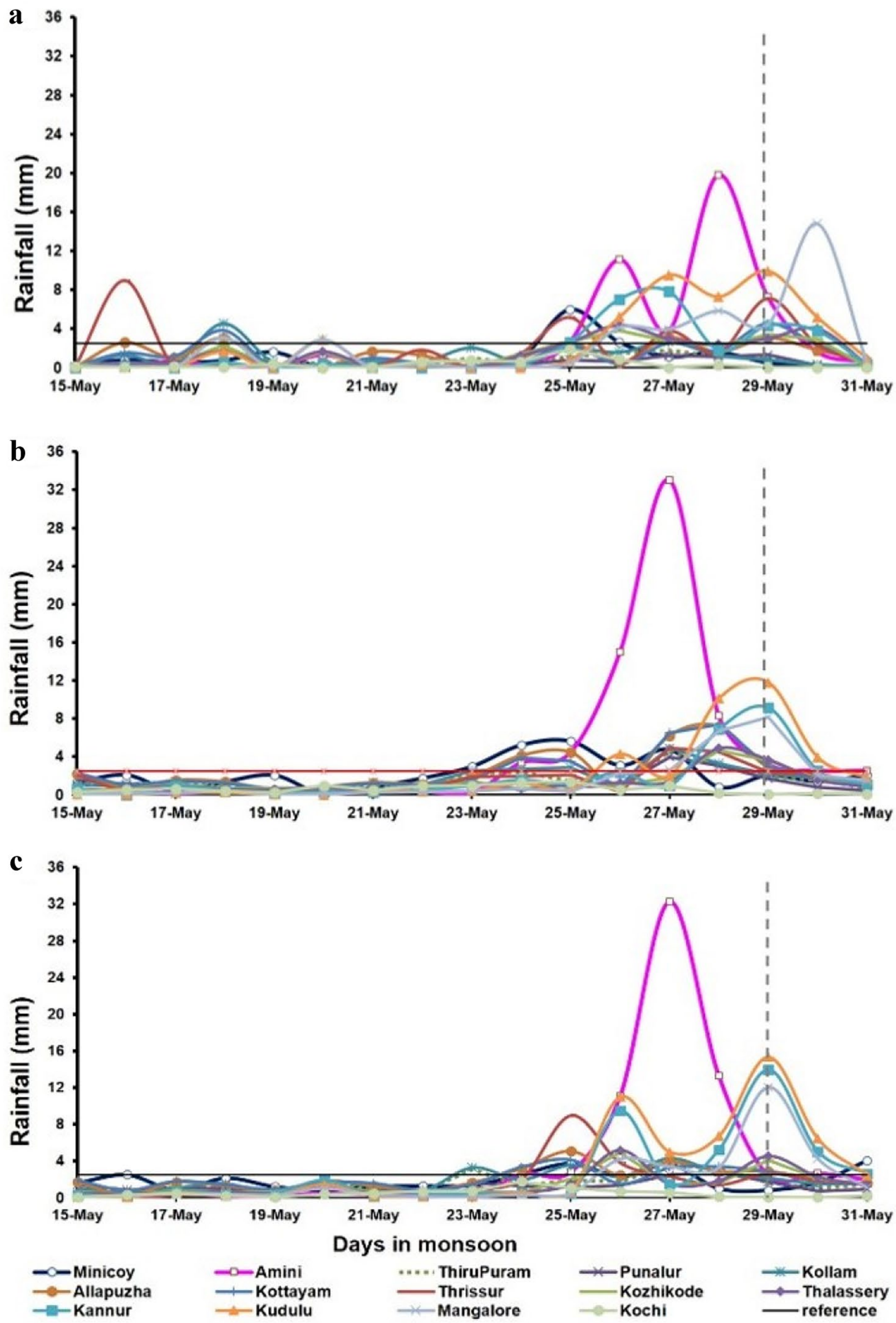


Fig. 2 The time series of rainfall (mm) during 15–31 May 2018 of 14 stations for **a** observations **b** NCUM 10-day model forecast, and **c** UKMO 5-day model forecast. The vertical line indicates the IMD monsoon onset date

maximum amount during 28–31 May. It is interesting to see that the rainfall intensity is more than 2.5 mm during the whole period of 15–31 May. The models clearly show a similar rainfall trend as of observations, and the onset date from NCUM and NEPS agrees with the observed onset date. It is also clear from these figures that the minimum threshold value of 2.5 mm rain has been considered to declare as the monsoon onset. The assessment of rainfall forecast carried out from NCUM and NEPS (mean) models can predict the onset (rainfall) on a regional scale with some useful skill level.

3.2 Based on wind field criteria

The mean zonal ***(U)*** wind speed (***kts***) at 925 hPa level averaged over 5°–10° N, 70°–80° E, and at 600 hPa level averaged over the 0°–10° N, 55°–80° E are presented in Table 1. Depth of the westerly/west-southwesterly wind components extended up to 600 hPa and from the equator to 10° N and 55°–80° E. The zonal wind speed over the area bounded by 5°–10° N, 70°–80° E are noted to be of the order of 7–10 m/s at 925 hPa level. From Table 1, it is found that the wind speed is at the order of 15–20 kts at the end of May. Ultimately from the table, we can conclude that the onset is on 29 May 2018.

3.3 Based on vertical moisture transport criteria

As suggested by [30], the changes in the moisture content before the onset over Kerala and total precipitable water content over the peninsular region covering 0°–15° N and 70°–95° E have been used for declaring the date of monsoon onset subjectively. [30] also proposed a criterion to assesses the Indian monsoon onset date, which can be obtained from the hydrological cycle. The criterion is based on the integral of specific humidity times the zonal wind vector from surface to 300 hPa level. It is known as the vertically integrated moisture transport (VIMT) and based on the large scale monsoon circulation, driven by the zonal and meridional gradients of rainfall and water vapour. The VIMT method is used for onset date prediction in the present study by using the model forecasts.

Figure 3a and b represent the spatial distribution of VIMT obtained from NCUM model analysis and forecast. The Fig. 3a corresponding to the model analysis valid for 29 May, and Fig. 3b resembling day10 forecast valid on 29 May based upon the 19 May initial condition. The VIMT (shading) and moisture transport components as vectors show the flow from the southern to northern hemisphere re-curving over the Arabian sea (Figs. 3a, b). The monsoon onset transition typically shows the monsoon current setup in the southwest of India coupled with enhanced moisture transport towards the Bay of Bengal region. During the onset phase, we noticed a lot of moisture convergence over Kerala and the tropical Indian Ocean. During the onset phase, [31] showed a lot of moisture transits from the Arabian Sea to peninsular India. The deep convection was noticed during the active monsoon phase over the Bay of Bengal and the eastern Arabian Sea regions from the divergent regions of the southern hemisphere and the Arabian Sea. The model 10-day VIMT forecast explains that the occurrence of onset on 29 May (Fig. 3b); the same can be validated from the model analysis (Fig. 3a), which also can be considered as observation. Here we have observed that the moisture is transported mostly northward into the Arabian Sea, while the other component was passing south of the Indian subcontinent and feeding the equatorial westerly circulation through Bay of Bengal.

3.4 Based on Radiation criteria

Basically, the surface temperature difference between the land and the ocean drives the Indian summer monsoon. [3] studied the onset over Kerala and the evolution of deep tropical convection and associated outgoing Long-wave Radiation (OLR) at the spatial and temporal scales using the mean maps. Sometimes the OLR values show fewer values, but these are considered as a proxy onset date. After excluding these proxy values, it is noticed that each year the onset date is close to 1 June. The INSAT-3D OLR values along with NCUM day 10 forecast OLR values averaged over a region (5°–10° N and 70°–75° E) during the period 15–31 May 2018 is presented as a bar chart (Fig. 4). The figure shows that OLR below 200 W/m^2 resulted on the onset date 27–28 May. For a few days, the OLR values show

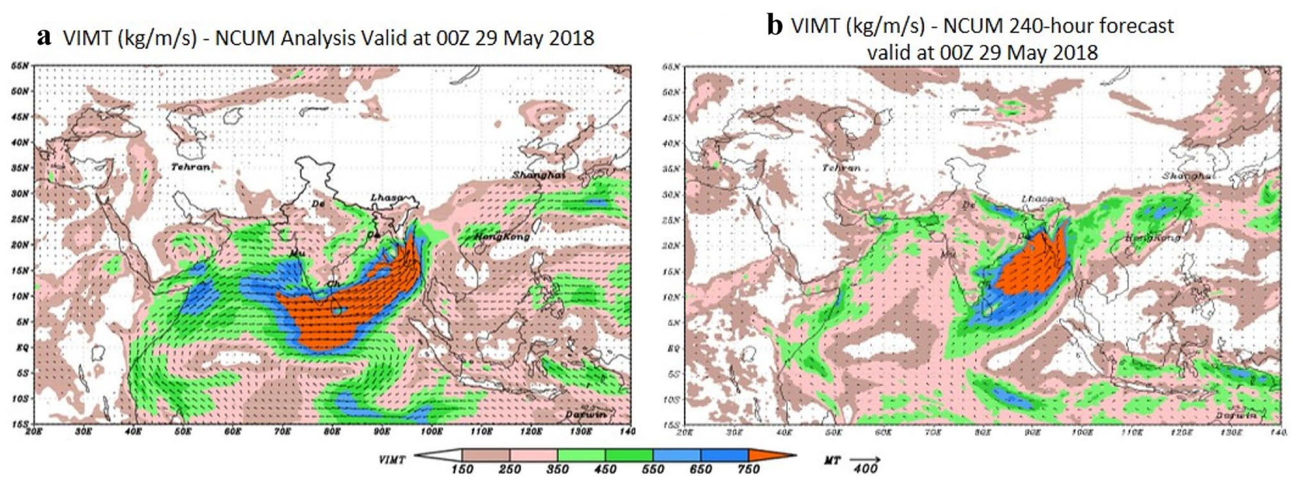


Fig. 3 The spatial distribution of NCUM Vertically Integrated Moisture Transport (VIMT, kg/m/s) for **a** analysis and **b** day 10 forecast valid at 00Z 29 May 2018

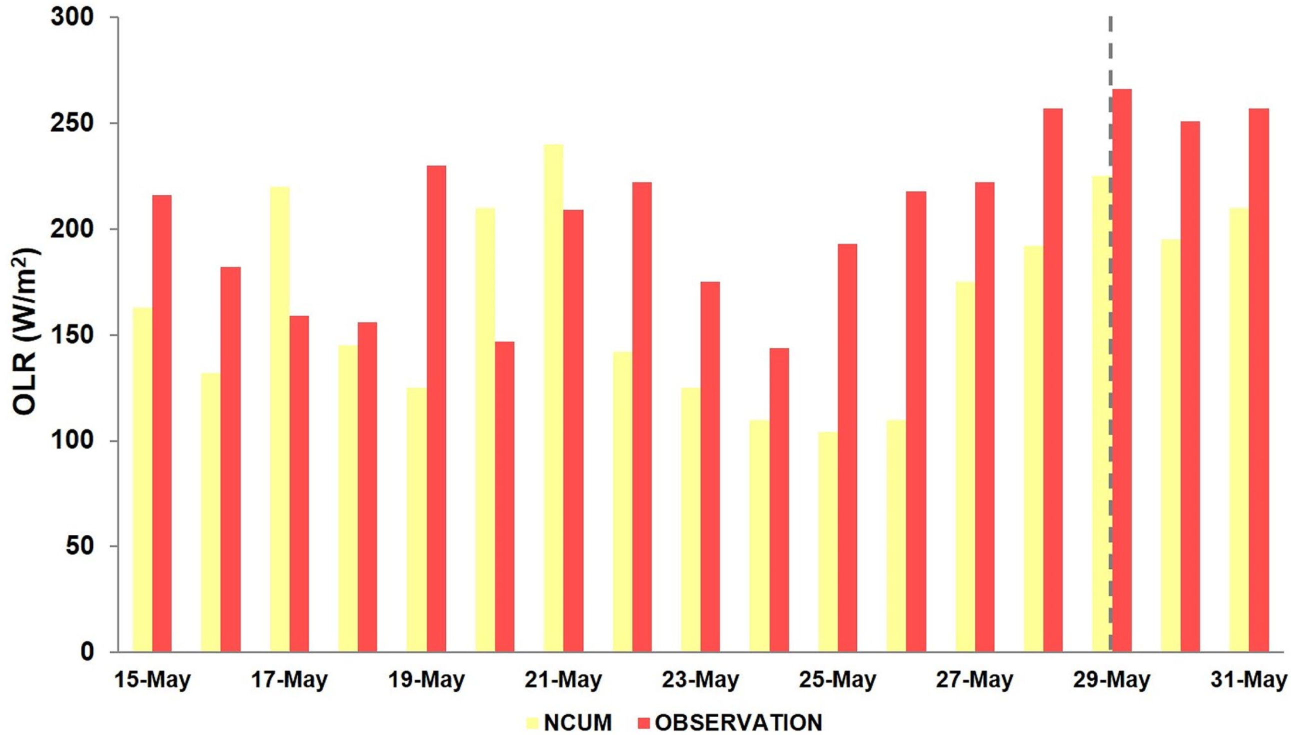


Fig. 4 Time series of NCUM 10-day forecasted outgoing long-wave radiation (OLR, W/m2) during 15–31 May 2018 along with INSAT-3D observations. The OLR is averaged over 5°–10° N and 70°–75° E. The vertical line indicates the IMD monsoon onset date

less than 200 W/m^2, but these days cannot be considered as the onset dates, since all the other criteria suggest 29 May; hence, those days are considered as bogus onset dates. As a by-product, the performance of the models' radiation scheme also validated for the cloudy region.

3.5 Based on zonal wind criteria

Figure 5 describes the onset circulation index or the daily monsoon index indicates based on the variation of Somali cross-equatorial low-level jet. [4] found that the onset date can be determined objectively by computing the sustained 850 hPa zonal wind (***U***) averaged over the southern Arabian Sea box (5°–15° N, 40°–80° E). This criterion is referred to as an objective circulation index to examine the onset date. There may be a time lag of one or two days between the increase in the wind speed and the increase in rainfall amount. The rapid establishment of the due westerlies is an excellent/practical parameter to correlate with the rainy season's abrupt commencement over the southern tip of the Indian peninsular region. The onset date is defined on the first day when the consecutive next six days also exceeds the threshold of 6.2 m/s for the onset circulation index. This onset circulation index meets the objective, simple, and representative of both the Kerala rainfall and associated large-scale circulation changes during the onset. The daily circulation index from NCUM 5 and 10-day forecasts shown in Fig. 5a, NEPS 1–5 day forecasts shown in Fig. 5b and NEPS 10-day forecasts of different ensemble member along with its ensemble mean shown in Fig. 5c for the period 15 May—5 June.

This circulation index shows that the UKMO analysis and forecast agree with the NCUM 5/ 10 days forecasts; but the 10-day forecast has a slightly lower magnitude following the similar trend (Fig. 5a). From the NEPS day-1 to day-5 forecasts and the analysis, it is observed that till 27 May, there are minor differences in the daily circulation index. Afterward, the analysis and all these forecasts show gradual increase, agreeing with onset date on 29 May (Fig. 5b). The circulation index from the NEPS 10-day forecast of the 11-ensemble members shows a similar pattern as of their control and ensemble mean, and especially from 24 May, all these follow the similar trend, agreeing with the onset date on 29 May 2018 (Fig. 5c). From the above analysis, we can conclude that the NCUM operational deterministic and ensemble forecasts could predict the circulation very well and, subsequently the monsoon onset. We also evaluated this method for a delayed onset year 2019 (onset date 7 June 2019), and a timely onset year of 2020 (onset date 1 June 2020) using the circulation index only. The NCUM analysis and NCUM

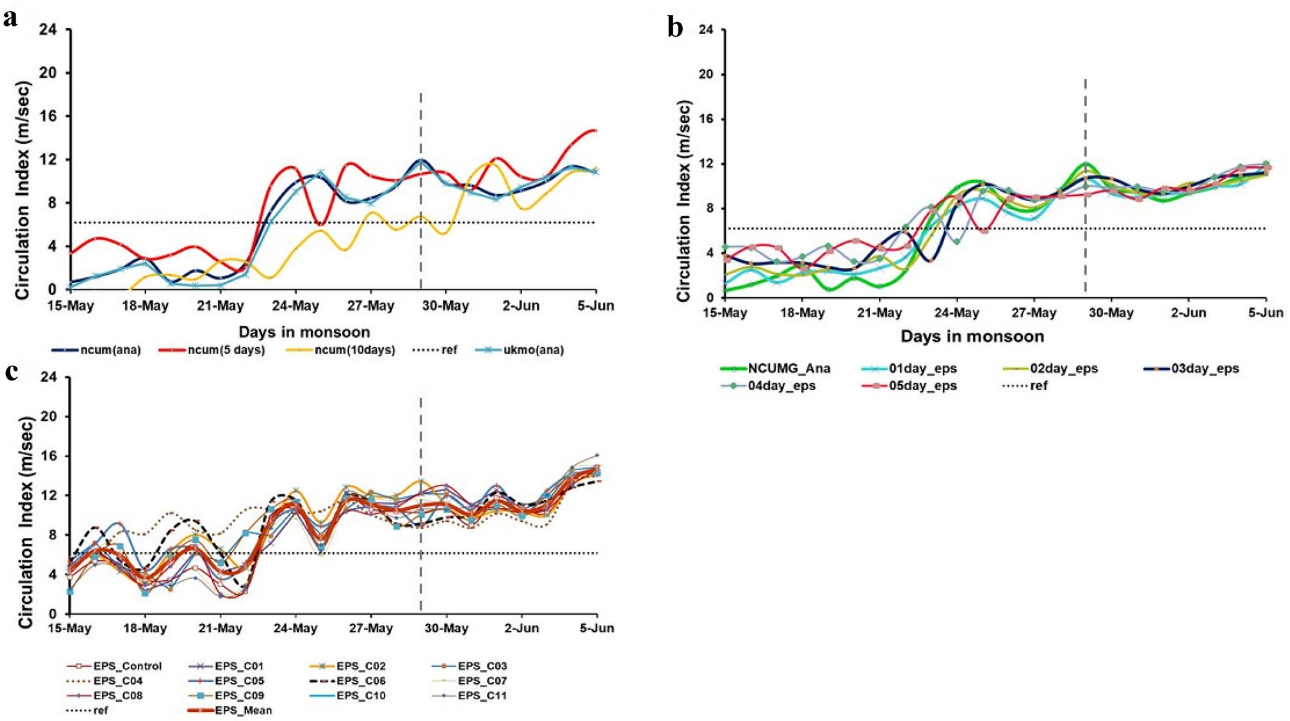


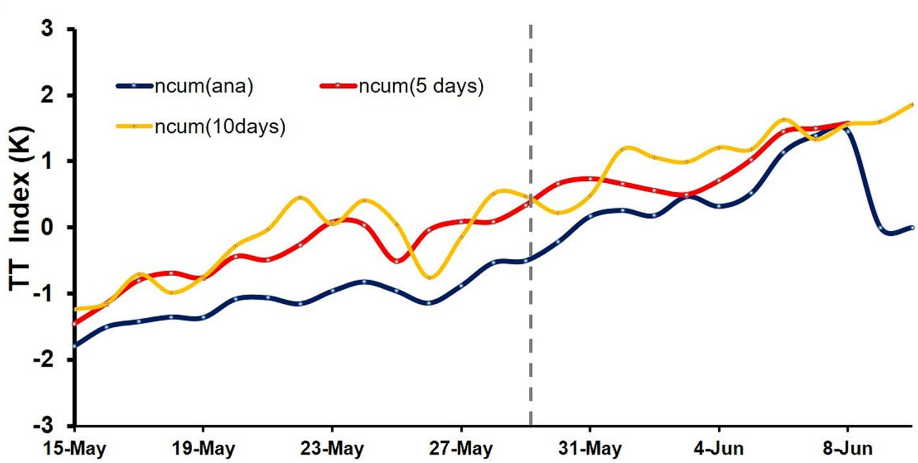
Fig. 5 Time series of daily monsoon index (m/s) during 15 May—05 June 2018 for **a** NCUM analysis, UKMO 5-day forecast, and NCUM 5-day and 10-day forecasts, **b** NEPS 1–5 days forecasts along with the analysis, and **c** NEPS 10-day forecasts along with the control and ensemble mean. The vertical line indicates the IMD monsoon onset date

10-day forecast circulation index show that the model could predict both the delayed and timely onset date, agreeing with the IMD estimated date (Fig. 9).

3.6 Based on Tropospheric temperature index criteria

The daily tropospheric temperature (TT) index variability during the Indian summer monsoon was studied by [32]. The index is the difference between the vertical mean temperatures between 700 and 300 hPa and area-averaged over a northern box region (10°–35° N, 30°–110° E) and a southern box region (15°S–10° N, 30°–110° E). Once the monsoon initiates, there is a movement in the heat release from the tropical Indian Ocean to the subtropics. The onset date is also defined as a day when the TT index sign changes from negative to positive. The TT index based on the NCUM model analysis, and (5 and 10-day) forecasts are shown in Fig. 6. The index changes its sign from negative to positive on 28 May for

Fig. 6 The time series of NCUM analysis, 5-day and 10-day forecast of troposphere temperature index (K) during 15 May—10 June 2018. The vertical line represents the IMD monsoon onset date



the NCUM model forecasts, where as the NCUM analysis shows on 30 May with an error of a day. Hence it is concluded that the NCUM model could capture the onset date for the 2018 monsoon.

The effects of changes in the lower tropospheric temperature at the time of onset were documented in [33]. The spatial distribution of the NCUM model predicted 850 hPa potential temperature (θ) overlayed with wind flow valid on 29 May along with the analysis is presented in Fig. 7. The time series for many days about the variability of potential temperature and winds have been analysed to conclude the onset date (Figure not shown). The potential temperature distribution at 850 hPa level shows that a large variation (gradient) is noticed between the Arabian Peninsula and the west coast of India. The gradient is caused by the strong westerly winds over the Arabian Sea. Subsequently, the potential temperature falls further near to west coast (Kerala) region nearing the onset of monsoon. This indicates that the NCUM predicted potential temperature distribution also agree the onset date on 29 May 2018.

3.7 Based on meridional wind shear criteria

[32] defined the index based on the meridional wind ***(V)*** shear between 850 and 200 hPa over the south Asian region (10°–30° N, 70°–110° E), related to Hadley cell. This index has been used for monitoring the onset and its advancement. Our analysis with the meridional wind also showing the onset date on 29 May 2018 (Figure not shown).

3.8 Based on kinetic energy criteria

The onset is always accompanied by a sudden increase in kinetic energy in the Arabian Sea around onset time. [30] suggested that a sharp rise of Kinetic Energy (KE) at 850 hPa over the Arabian Sea region (0°-19.5° N and 55.5°-75° E) indicates monsoon's onset over India. We also examined the onset date based on the KE (Fig. S1), and our study confirmed the onset date on 29 May 2018.

4 Rainfall distributions

Indian summer monsoon onset is a process with sudden changes in rainfall patterns; upper and lower level circulations, moisture availability, kinetic energy, etc. The spatial distribution of rainfall from observations, UKMO 5-day forecast, and NCUM 5 and 10-day forecasts valid on 29 May 2018, are shown in Fig. 8. The observed rainfall (Fig. 8a) shows more than 2 cm over the west coast of India, and a similar rainfall pattern is noticed in the UKMO 5-day forecast (Fig. 8c), and NCUM 5-day forecast (Fig. 8d), NCUM 10-day forecast (Fig. 8b). The rainfall bands off the west coast and over the Bay of Bengal region show more than 16 cm in observations, whereas the models underpredicted this rainfall. These figures clearly show that the models could forecast well with 5 and 10 days lead time. A southward shift (bias) of rainfall in the Arabian Sea is observed in both UKMO and NCUM 5-day forecasts, whereas it is further southward with NCUM 10-day forecast. UKMO 5-day rainfall forecast shows another spell over Madhya Maharashtra and Marathwada regions as false alarm. The heavy rainfall band (deep convection) in

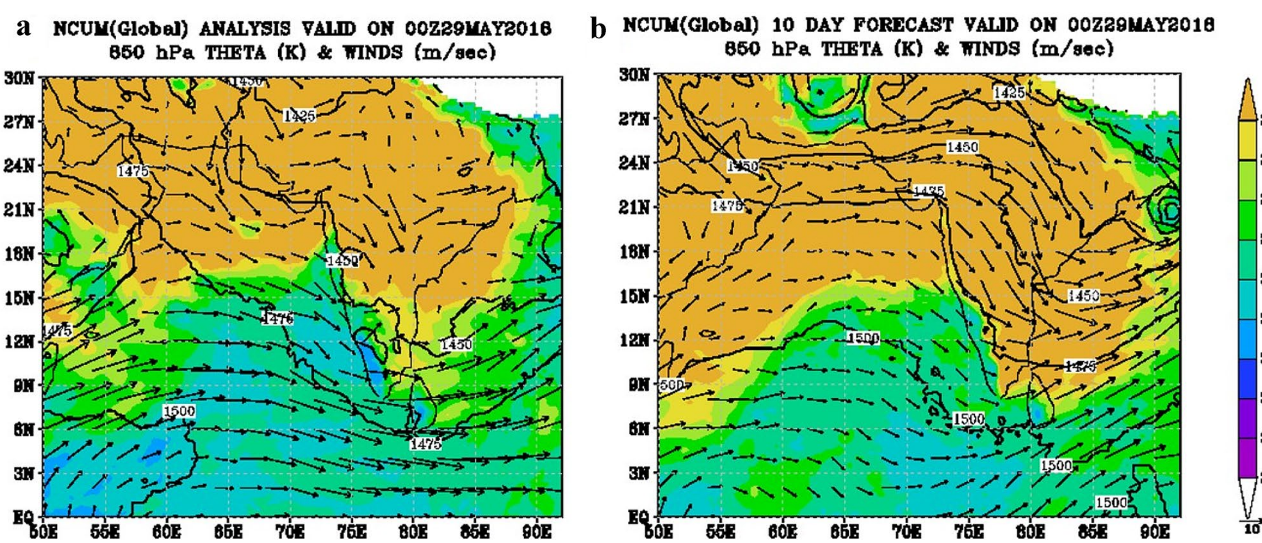


Fig. 7 The spatial distribution of NCUM potential temperature (K, shaded) at 850 hPa overlayed with geo-potential height (m) and the wind vectors valid on 29 May 2018 for **a** analysis, and **b** NCUM 10-day forecast

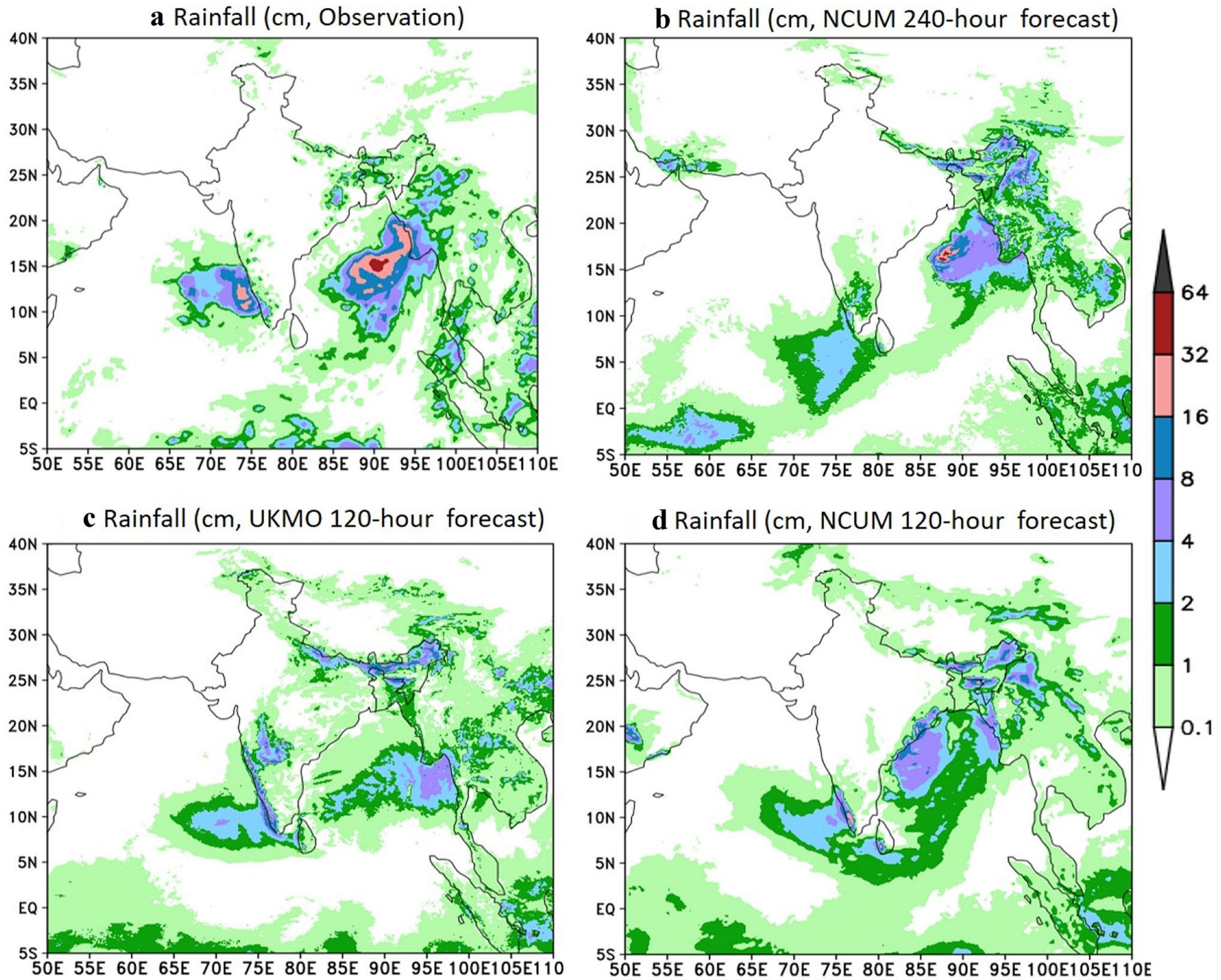


Fig. 8 The spatial distribution of rainfall (cm) of **a** observation, **b** NCUM 10-day forecast, **c** UKMO 5-day forecast, and **d** NCUM 5-day forecast valid at 00Z 29 May 2018

an east–west direction near India's southern tip before the onset has reported the persistent and widespread rainfall over Kerala. Overall, the UKMO and NCUM model forecasted rainfall amount more than 2 cm over Kerala region agreeing with the observations, subsequently the onset criteria based on station rainfall (> 2.5 mm) over Kerala region. These figures clearly show that the date of onset is on 29 May 2018. Here we can observe that a strong moisture convergence (Fig. 3) over the Indian Ocean and Indian landmass gradually extending to the western Pacific are also in agreement with the circulation and rainfall characteristics during onset time. From the above analyses, it would be concluded that following the above all criteria, the results show that the onset date modestly agreed with the reality of 29 May 2018.

5 Conclusions

The global operational models that predicted the onset dates of the Indian summer monsoon over Kerala are presented in this study. Here we have utilized the NCMRWF global analysis and forecasting system's datasets (analysis, 5/10 days forecasts from NCUM, NEPS), UKMO analysis and 5-day forecasts. For the year 2018, we have followed the IMD criterion to predict the monsoon onset date. These criteria are based on (i) observed rainfall over the 14 stations (ii) zonal (***U***) and meridional (***V***) components of wind speed and (iii) amount of outgoing radiation. The results show that 12 stations (Thalassery, Kannur, Kudulu, Mangalore, Minicoy, Amini, Thiruvananthapuram, Kollam, Allapuzha, Kozhikode, Kottayam, Thrissur) predicted rainfall more than 2.5 mm threshold value during 28–29 May 2018, and declared onset on 29 May 2018.

Also some more objective methods based upon the model forecast variables of (i) rainfall (ii) outgoing radiation (iii) potential temperature (iv) integrated vertical moisture (v) monsoon indices with zonal wind (vi) raise in tropospheric temperature, etc. are being used for onset date estimation. The spatial distribution of rainfall with 5 to 10 days lead time clearly demonstrates monsoon's onset over the Indian sub-continent. Early indication of an event with at least 10 days lead time helps the operational monsoon forecaster. Since the model has reasonably well captured the inter-annual variability of the onset date, it is interesting to monitor the model's performance in all the situations like early (2018), delay (2019) and timely (2020) onset. Figure 9 shows the daily monsoon index for delayed (2019) onset (Fig. 9a) and timely (2020) onset (Fig. 9b). The indices show that the NCUM 10 days predicted (IMD estimated) onset dates are on 07 June 2019 (08 June 2019) and 01 June 2020 (01 June 2020), respectively. From this analysis, the NCUM model forecasts have a significant value at medium-range time scales for monsoon onset prediction for all types of monsoon onset (early, on time, and delayed). Also, NCMRWF high-resolution models, NCUM, and NEPS's prediction capability with new data assimilation scheme in the medium range scale has been in operational since the year 2018.

The models could predict the monsoon onset over Kerala and north-western parts of India with 7 to 10 days lead time. The ensemble forecasts performed very well in predicting the monsoon onset. The ensemble model forecasts also provide the probability of rainfall over a region, which helps the forecaster along with confidence. It was also noted that the onset of monsoon should re-defined by considering changes in large-scale thermodynamic and dynamic parameters. This study also verified the new-onset dates/isochrones introduced by the national weather agency IMD [11]. The new onset date announced [11] with observed gridded rainfall has been justified with the model rainfall.

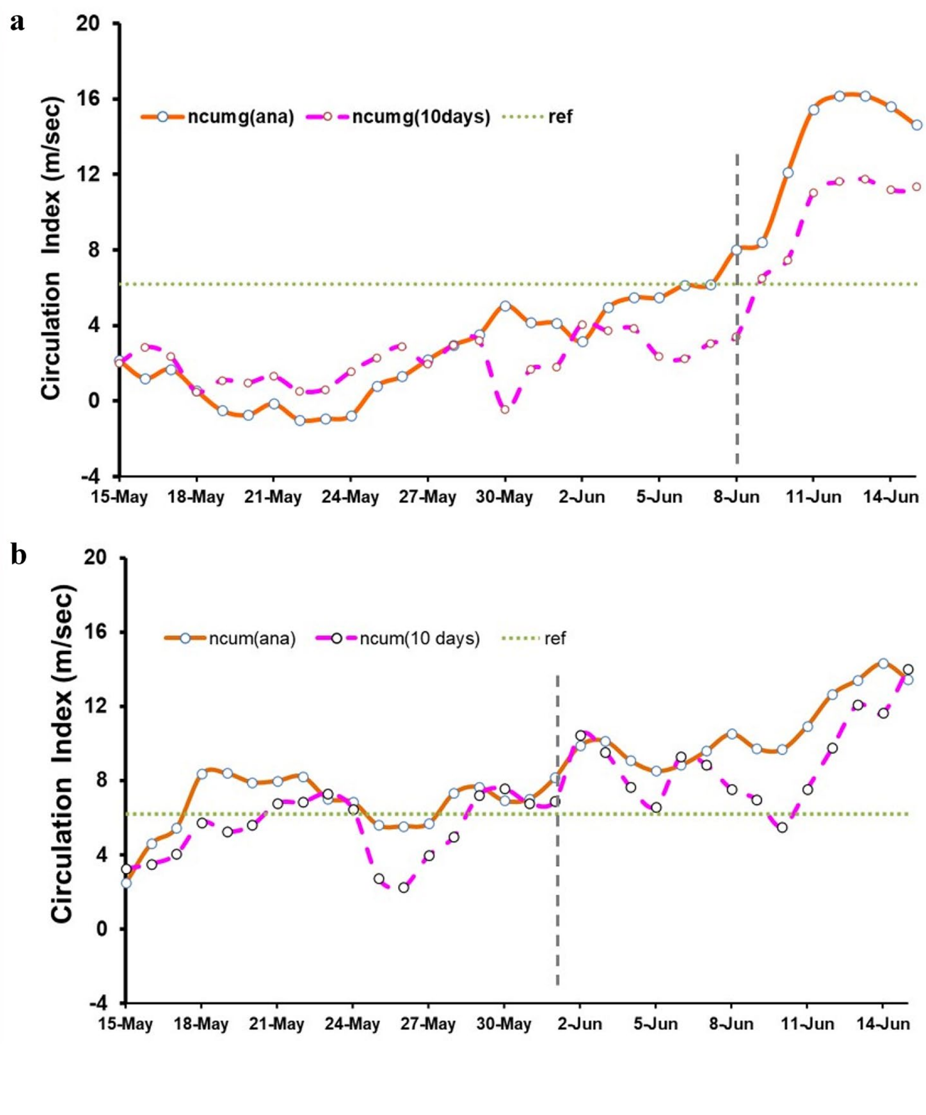


Fig. 9 Time series of daily monsoon index (m/s) **a** NCUM analysis, 10-day forecast valid for 15 May—15 June 2019, and **b** NCUM analysis, 10-day forecast valid for 15 May—15 June 2020. The vertical line represents the IMD monsoon onset date

Table 1 The mean zonal (U) wind speed at 925 hPa level over the Oceanic area 5º–10º N, 70º–80ºE and winds at 600 hPa level over the 0–10ºN, 55º–80º E

Date	U925 hPa (kts)	U600 hPa (kts)
15 May	4.84	1.89
16 May	6.11	2.03
17 May	7.78	2.57
18 May	6.19	2.60
19 May	8.90	3.48
20 May	6.35	0.4
21 May	10.16	11.79
22 May	11.19	9.41
23 May	4.29	3.81
24 May	11.08	6.91
25 May	12.49	9.57
26 May	12.84	12.20
27 May	11.91	9.13
28 May	13.99	5.68
29 May	14.48	11.43
30 May	12.84	11.30
31 May	10.66	11.75

Our study also confirms the existing monsoon onset mechanism, where the monsoon flow starts from southern hemisphere as southeasterlies at the lower levels (850 hPa). These south easterlies turned into south-westerlies crossing the equator through the Arabian Sea and transported a lot of moisture (Fig. 3) to the Indian subcontinent. This mechanism through which reduction of potential temperature and increasing wind speed at 850 hPa level (Fig. 7) contributing to the onset of the monsoon over Kerala (Fig. 1).

The uncertainly about the onset dates 'double onset', 'bogus onset', 'false onset' are totally eliminated. Mainly this paper describes the onset calculation based upon medium-range time scale (5–10 days) forecasts. However, we have adopted the analysis (model initial conditions) for verification and diagnostic purposes and 1–10 days forecasted meteorological variables. The model's skill was found reasonably well with 10-day forecasts, predicting the onset date on 29 May for 2018, 8 June for 2019, and 1 June for 2020. The deterministic and ensemble model forecasts could predict India's monsoon onset within 1 day error at medium-range time scales. The double onset issues will be investigated more quantitatively, considering the local/ regional circulations in models and integration of various kinds of observations will be taken up as a future study. The methodology also will be adopted to compute the onset date using the 40 years of NCMRWF regional reanalysis data will be taken up as a further study to understand the versatility of the objective methods.

Acknowledgements The authors are very much thankful to the Head, NCMRWF for his continuous support. The authors are also thankful to Director General of IMD for providing the datasets and sharing the weather bulletins. The comments and suggestions by the IMD scientists also helped to enhance the quality of the paper. Theauthors thank their other colleagues at NCMRWF for stimulating discussions in finalizing the paper.

Availability of data and material The dynamical models NCUM, Met-office analysis and forecasts data sets and conventional observations are utilized by the lead author on daily basis. These data sets are examined, and the indices are calculated for the year 2018, 2019 and 2020.

Code availability All the onset dates are computed by the software programmers written in Fortran language.

Declarations

Conflict of interest On behalf of all authors the corresponding author states that there is no conflict of interest.

References

1. Parthasarathy B, Munot AA, Kothawale DR (1994) All India monthly and seasonal rainfall series: 1871–1993. Theor Appl Climatol 49(4):217–224
2. Maheswar P, Rao AS, Ankur S, Ashish D, Kiran S, Shameera KS (2017) Prediction of Indian summer-Monsoon onset variability: a season in advance. Sci Rep 7(1):1–14
3. Joseph PV, Eischeid JK, Pyle RJ (1994) Interannual variability of the onset of the Indian summer monsoon and its association with atmospheric features, El Nino, and sea surface temperature anomalies. J Clim 7(1):81–105
4. Findlater J (1969) A major low level air current near the Indian Ocean during the northern summer. Q J R Meteorol Soc 95:362–380
5. Wang B, Ding Q, Joseph PV (2009) Objective definition of the Indian summer monsoon onset. J Clim 22(12):3303–3316
6. IMD (1943) Climatological Atlas for Airman. India Meteorological Department, Pune, p 100
7. Ramdas LA, Jagannathan P, Rao SG (1954) Prediction of date of establishment of southwest monsoon along west coast of India. Indian J Meteorol Geophys 5:305–314
8. Reddy SJ (1977) Forecasting the onset of southwest monsoon over Kerala. Indian J Meteorol Geophys 28:113–114
9. Rajeevan M, Dube DP (1995) Long range prediction of monsoon onset over Kerala. Mausam 46:287–290

10. Puranik S, Sinha RKC, Sen PN, Kumar P (2013) An index for predicting the onset of monsoon over Kerala. Curr Sci 105(7):954–961
11. Pai DS, Bandgar A, Devi S, Musale M, Badwaik MR, Kundale AP, Gadgil S, Mohapatra M, Rajeevan M (2020) Normal dates of onset/progress and withdrawal of southwest monsoon over India. Mausam 71(4):553–570
12. Krishnamurthi TN, Ardanuy P, Ramanathan Y, Pasch R (1981) On the onset vortex of the summer monsoon. Mon Weather Rev 109(2):344–363
13. Soman MK, Kumar KK (1993) Space time evolution of meteorological features associated with the onset of Indian summer monsoon. Mon Weather Rev 121:1177–1194
14. Li C, Michio Y (1996) The onset and interannual variability of the Indian summer monsoon in relation to land-sea thermal contract. J Clim 9(2):358–375
15. Goswami BN, Venugopal V, Sengupta D, Madhusoodhan MS, Prince X (2006) Increasing Trend of extreme rain events in a warming environment. Science 314:1442–1445
16. Ravindra Babu S, Ratnam MV, Basha G, Krishnamurthy BV (2019) Indian summer monsoon onset signatures on the tropical tropopause layer. Atmos Sci Lett 20:e884. https://doi.org/10.1002/asl.884
17. Singh S, Ghosh S, Sahana AS, Vittal H, Karmakar S (2017) Do dynamic regional models add value to the global model projections of Indian monsoon? Clim Dynam 48(3):1375–1397. https://doi.org/10.1007/s00382-016-3147-y
18. Joseph S, Sahai AK, Abhilash S, Chattopadhyay R, Borah N, Mapes BE, Rajeevan M, Kumar A (2015) Development and evaluation of an objective criterion for the real-time prediction of Indian summer monsoon onset in a coupled model framework. J Clim 28(15):6234–6248. https://doi.org/10.1175/JCLI-D-14-00842.1
19. Pattnayak KC, Panda SK, Saraswat V, Dash SK (2019) How good is regional climate model version 4 in simulating the monsoon onset over Kerala. Int J Climatol 39(4):2197–2208. https://doi.org/10.1002/joc.5945
20. Chakraborty P, Sarkar A, Bhatla R, Singh R (2020) Assessing the skill of NCMRWF global ensemble prediction system in predicting Indian summer monsoon during 2018. Atmos Res 248:105255. https://doi.org/10.1016/j.atmosres.2020.105255
21. Sharma K, Ashrit R, Ebert E, Mitra AK, Bhatla R, Iyengar G, Rajagopal EN (2018) Assessment of met office unified model (UM) quantitative precipitation forecasts during the indian summer monsoon. J Earth Syst Sci 128(1):4. https://doi.org/10.1007/s12040-018-1023-3
22. Rajagopal EN, Iyengar GR, George John P, Gupta MD, Mohandas S, Siddharth R, Chourasia M, Prasad VS, Singh A, Sharma K, Ashish A (2012) Implementation of Unified Model based Analysis-Forecast System at NCMRWF. NCMRWF Technical Report, NMRF/TR/2/2012, Noida, Govt. of India, p.45
23. Sarkar A, Chakraborty P, George JP, Rajagopal EN (2016) Implementation of Unified Model based Ensemble Prediction System at NCMRWF (NEPS). NCMRWF Technical Report, NMRF/TR/02/2016, Noida, Govt. of India, p.26
24. Walters D (2017) The met office unified model global atmosphere 6.0/6.1 and JULES global land 6.0/6.1 configurations. Geosci Model Dev 10:1487–1520. https://doi.org/10.5194/gmd-10-1487-2017
25. Rajeevan M, Bhate J, Kale JD, Lal B (2006) High resolution daily gridded rainfall data for the Indian region: analysis of break and active monsoon spells. Curr Sci 91(3):296–306
26. Mitra AK, Bohra AK, Rajeevan MN, Krishnamurti TN (2009) Daily Indian precipitation analysis formed from a merge of rain-gauge data with the TRMM TMPA satellite–derived rainfall estimates. J Meteorol Soc Jap 87A:265–279
27. Joseph PV, Sooraj KP, Rajan CK (2006) The summer monsoon onset over process over south Asia and an objective method for the date of monsoon onset over Kerala. Int J Climatol 26(13):1871–1893
28. Mohanty UC, Dube SK, Singh MP (1983) A study of heat and moisture budget over the Arabian Sea and their role in the onset and maintenance of summer monsoon. J Meteorol Soc Jap 61(2):208–221
29. Rajan D, Iyenger GR (2013) Dynamical monsoon indices. Int J Earth Sci Eng 6(5):1000–1011
30. Ramesh KJ, Swati B, Begum ZN (1996) Objective determination of onset advancement and withdrawal of the summer monsoon using large-scale forecast of global spectral model over India. Meteorol Atmos Phys 61(3–4):137–151
31. Fasullo J, Webster PJ (2003) Hydrological definition of Indian monsoon onset and withdrawal. J Clim 16(19):3200–3211
32. Goswami BN, Xavier PK (2005) ENSO control on the South Asian monsoon through the length of the rainy season. GeophyS Res Lett 31(18):L18717. https://doi.org/10.1029/2005GL023
33. Taniguchi K, Rajan D, Koike T (2010) Effect of the variation in the lower tropospheric temperature on the wind onset of the Indian summer monsoon. Meteorol Atmosp Phys 106(1–2):75–94